Rec'd PCT/PTO 10 MAY 2005

Power converter

The invention relates to a power converter comprising an inductor for receiving energy from a power supply, and connected to the inductor an output capacitor for providing an output voltage. The invention relates equally to a method for operating such a power converter.

Power converters of this kind are known from the state of the art. They comprise, for example, conventional buck converters, which are used for DC (direct current) to DC down-conversions.

A buck converter comprises a series connection of an inductor and an output capacitor as output filter, and switching means connecting the series connection with a DC voltage source. The switching means are controlled such that a desired output voltage is obtained across the output capacitor. The output capacitor thus provides a regulated voltage output for a load.

A common problem occurring with buck converters are voltage ripples at the output, which are usually reduced by increasing the number of output capacitors. The required large number of output capacitors, however, makes the output filter to one of the most expensive parts of the power supply.

While buck converters can be used as single converters, alternatively a plurality of buck converters may be used in a so called multiphase converter. The principle of multiphase converters allows to reduce the output voltage ripple under steady state conditions. Thus the number of output capacitors might be reduced by using a multiphase converter.

Still, the voltage ripple at the output of a buck converter is determined mainly by the voltage drops and jumps associated with load transients. The reason for an increase of the output voltage whenever the load current is reduced is the energy stored in the buck inductor. This energy is delivered to the output capacitors, also in the

case of multiphase converters. Therefore, the load steps reducing the load current as defined by a specific application determine the amount and type of output capacitors which are needed to stay within an allowed voltage tolerance.

Buck converters are used in particular for DC-DC down-conversions for high speed digital ICs (integrated circuits), like high end Pentium® processors for PCs (personal computers). Especially high speed digital ICs exhibit very steep load transients. At the same time, the specification of these ICs request very severe voltage tolerance limits. The supply voltage of high speed digital ICs clearly tends to lower voltages reaching less than 1.5V in the near future. Thus, a voltage control is of particular importance for such high speed applications.

Also other kinds of conventional converters require a high number of expensive capacitors in order to keep the output voltage within acceptable bounds.

In patent application WO 01/59917, it has been proposed to use an inductance, which is composed of a first inductor and a second inductor connected in parallel to each other. The branch comprising the second inductor comprises in addition a switch, which is only closed during load transients. This solution enables a reduction of voltage ripples, but due to the characteristics of an inductor, the reaction time is rather slow, since the current through the branch is only build up slowly.

It is an object of the invention to provide a power converter with a reduced number of capacitors, which compensates quickly for a reduction of load at the voltage output of the converter.

A power converter is proposed, which comprises an inductor for receiving energy from a power supply, and connected to the inductor an output capacitor for providing an output voltage. Further, the proposed power converter comprises an additional current path arranged in parallel either to the inductor or to the capacitor. The additional current path can be opened and closed. The additional current path is formed such that a current flowing through it reaches basically immediately a desired value

when the additional current path is opened. Feedback means are moreover provided for opening the additional current path, when the output voltage across the output capacitor reaches a predetermined maximum value. The feedback means may, but do not have to, comprise processing means for controlling the additional current path.

Moreover, a corresponding method is proposed.

The invention proceeds from the consideration that the number of output capacitors can be decreased by removing energy stored in the inductor during the load reduction. The stored energy is removed according to the invention by using an additional current path, or transient shunt. The proposed transient shunt allows to minimize the number of output capacitors in the converter, since the influence of load steps due to a reduction of the load is canceled.

It is thus an advantage of the invention that it enables a reduction of the capacitance down to the limit determined either by the turn-on transients or by the normal operation.

In contrast to the solution according to document WO 01/59917, the proposed power converter is moreover able to react immediately to a detected reduction of the connected load. Since a defined additional current path is provided, instead of an additional inductor, the compensation is not subject to a delay due to the gradual increase of the current through the additional inductor, as in document WO 01/59917.

Preferred embodiments of the invention become apparent from the dependent claims.

The additional current path may comprise any components which provide a controlled impedance and thus a defined current path, i.e. a path on which the current is set immediately. The additional current path may be in particular a low impedance path or comprise a current source.

In one embodiment, the additional current path can only be opened and closed, e.g. opened for a predetermined time or opened until a predetermined voltage over the output capacitor is reached. In the latter case, a hysteresis is achieved.

In another embodiment, the additional current path can be regulated in addition when open, for instance based on the current through the inductor or based on the voltage across the capacitor.

The invention can be employed for compensating for any reduction of load, i.e. as well for a partial reduction as for a complete turn-off of the load.

The invention can moreover be employed for various kinds of power converters. The invention can be employed for instance for buck converters, but equally for other down-converters, for boost converters as well as for other kinds of up-converters, and also for combined boost/buck converters and other kinds of combined up/down converters.

The invention can further be employed as well for single converters as for multiphase converters.

The invention can be employed in particular for point-of-load DC-DC converters for all high-speed ICs, currently especially for Pentium®-like processor cores and for DSPs (digital signal processors).

The invention will now be described in more detail by way of example and with reference to the attached drawings, wherein:

Fig. 1 is a circuit diagram of a buck converter with an indication of two different possible locations for an additional current path according to the invention;

Fig. 2 is a circuit diagram of a first embodiment of a buck converter according to the invention using a current source in an additional current path;

Fig. 3 is a circuit diagram of a second embodiment of a buck converter according to the invention using a low impendance path as additional current path; and

Fig. 4 is a circuit diagram of a third embodiment of a buck converter according to the invention using a low impendance path as additional current path.

Figure 1 is a basic circuit diagram of a buck converter with an indication of possible locations for an additional current path according to the invention.

The buck converter comprises a voltage source 1. A first terminal of the

voltage source 1 is connected to the drain D1 of a first MOSFET (metal-oxide semiconductor field-effect transistor) 2, while the second terminal of the voltage source 1 is connected to ground. The source S1 of the first MOSFET 2 is further connected to the drain D2 of a second MOSFET 3. The source S2 of the second MOSFET 3 is connected to ground. A respective diode 4, 5 is connected in parallel to each of the two MOSFETs 2, 3. The respective gate G1, G2 of the MOSFETs 2, 3 is connected to a control unit (not shown), which is responsible for switching the MOSFETs 2, 3.

In addition, a first connection of an inductor 6 is connected between the source S1 of the first MOSFET 2 and the drain D2 of the second MOSFET 3. The second connection of the inductor 6 is connected to a first connection of an output capacitor 7. The second connection of the output capacitor 7 is connected to ground.

The voltage across the output capacitor 7 can be provided as regulated voltage supply to a load. The output voltage is regulated by adjusting the switching of the MOSFETs 2, 3 by means of the control unit.

According to the invention, an additional current path 11, 12 is provided in parallel to the inductor 6 and/or in parallel to the capacitor 7. The additional current path 11, 12 is opened, whenever a load connected to the output capacitor 7 is turned off. Thereby, the energy stored in the inductor 6 can be removed via the additional current path. The direction of the current on the possible additional current paths is indicated by arrows.

Figure 2 presents a first embodiment of a buck converter according to the invention including an additional current path. The buck converter corresponds to the buck converter described with reference to figure 1, and the same reference signs were used for corresponding components. Here, a load 8 connected to the output capacitor 7 is depicted as well. For providing the additional current path 12 of figure 1, a controlled current source 22 is connected in parallel to the output capacitor 7. The current source 22 is arranged such that it is able to provide an additional current in the direction of ground. A control input of the current source 22 is connected to feedback means. The feedback means constitute a connection to the voltage output of the buck converter and may include the control unit.

As long as the load 8 is turned on, the current path comprising the

controlled current source 22 is not opened, and the buck converter operates like a conventional buck converter. As soon as the load 8 is turned off, however, the controlled current source 22 is activated, in order to reduce the energy in the inductor 6. Turning off of the load 8 leads to an increase in the voltage over the output capacitor 7. The feedback means therefore open the additional current path by activating the current source 22, whenever the output voltage reaches a predetermined, application dependent maximum limit.

Once the current source 22 is activated, it is regulated by the output voltage such that the output voltage is maintained at a predefined limit, which is the same as regulating the current into the capacitor 7 to zero. Alternatively, the current source 22 could be regulated to follow the inductor 6 current, in order to regulate the current into the combination of capacitor 7 and load 8 to zero. In another alternative, a fixed amount of current could be subtracted by the current source 22. This fixed amount has to be equal to or larger than the worst case maximum inductor current remaining when the predetermined limit for the output voltage is reached. The current could be drawn either for a certain time, which means that a certain amount of energy is not only drawn from the inductor 6 but also from the output capacitor 7. Further, the current could be drawn until the output voltage has dropped below a certain value. Thereby, a hysteretic control of the current is achieved.

Figure 3 presents a second embodiment of a buck converter according to the invention including an additional current path. The buck converter corresponds again to the buck converter described with reference to figure 1, and the same reference signs were used for corresponding components. A load 8 is connected again to the output capacitor 7. For providing the additional current path 12 of figure 1, a variable resistor 32 is connected in parallel to the output capacitor 7. Thereby, a low impedance path is achieved as additional current path. Like in the embodiment of figure 2, the additional current path is opened, when the voltage over the output capacitor 7 reaches a predetermined value. The variable resistor 32 can be controlled in several ways, just as described for the current source 22 of figure 2. A control input of the resistor 32 is connected to feedback means, which open the current path by reducing the resistance of the resistor 32. The feedback means constitute again a connection to the voltage output

of the buck converter and may include the control unit.

For a hysteretic control of the output voltage, the resistor 32 can be realized for instance with a MOSFET having a certain on-resistance. This MOSFET is turned on when a predetermined voltage limit over the output capacitor 7 is reached. This voltage limit is set such that it is reached when the load 8 is turned off. As a result, the complete inductor current is shunted through this on-resistance. The on-resistance has to be low enough to shunt the current under all circumstances. Thus, normally, also a current will flow out of the output capacitor 7 through the MOSFET. When the voltage drops below a certain second predetermined threshold value, the MOSFET is turned off again. The remaining current in the inductor will then start to charge the output capacitor 7 again, leading eventually to additional shunting actions.

Figure 4 presents a third embodiment of a buck converter according to the invention including an additional current path. The buck converter corresponds again to the buck converter described with reference to figure 1, and the same reference signs were used for corresponding components. A load 8 is connected again to the output capacitor 7. For providing the additional current path 11 of figure 1, a variable impedance is connected in parallel to the inductor 6. Thus, again a low impedance path is achieved as additional current path.

The variable impedance is realized with a MOSFET 41 and two diodes 42, 43, diode 43 being the body diode of MOSFET 41. A series connection of the two diodes 42, 43 is connected in parallel to the inductor 6. The forward direction of the two diodes 42, 43 is opposite to each other. MOSFET 41 is connected in parallel to the diode 43 having its forward direction in direction of the output capacitor 7. More specifically, the drain D3 of MOSFET 41 is connected to the connection of the diode 43 which is closer to the output capacitor 7, while the source S3 of MOSFET 41 is connected to the connection of the diode 43 which is farther away from the output capacitor 7. The gate G3 of MOSFET 41 is connected to feedback means. The feedback means constitute a connection to the voltage output of the buck converter and may include the control unit.

When the output voltage reaches a predetermined value, a voltage is applied by the feedback means to the gate G3 of MOSFET 41. Thereby, the inductor 6

is short-circuited in one direction with a specific resistance via MOSFET 41 and diode 42. The inductor current thus starts to circulate. The energy in the choke will decrease due to losses in the MOSFET 41 and the diode 42. If the current drops to zero, the entire energy is dissipated in the MOSFET 41 and the diode 42.

In case the load 8 is turned on again and thus requires energy again, while the current is still circulating, the remaining energy can be used to start supplying the load 8. To this end, diode 42 may be realized as Schottky diode or by a further low ohmic MOSFET. Thus, the decay in the inductor current can be decreased and more current will remain in the inductor to be supplied to the load 8 again. A further MOSFET is turned on in case the load 8 is turned on again, while MOSFET 41 is still on, resulting in an additional short-circuit in the opposite direction. Additionally, such a further MOSFET could be turned on in case the load 8 is rapidly turned on again.

It is to be noted that the described embodiments of the invention constitute only some of a variety of possible embodiments. It is further understood that any of the presented embodiments of the invention can be varied and supplemented in many ways.